TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 514

EFFECT OF COMBUSTION-CHAMBER SHAPE ON THE PERFORMANCE OF A PRECHAMBER COMPRESSION-IGNITION ENGINE

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Washington
December 1934

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SUMMARY

The effect on engine performance of variations in the shape of the prechamber, the shape and direction of the connecting passage, the chamber volume using a tangential passage, the injection system, and the direction of the fuel spray in the chamber was investigated using a 5 by 7 inch single-cylinder compression-ignition engine. The results show that the performance of this engine can be considerably improved by selecting the best combination of variables and incorporating them in a single design. The best combination as determined from these tests consisted of a disk-shaped chamber connected to the cylinder by means of a flared tangential passage. The fuel was injected through a single-orifice nozzle directed normal to the air swirl and in the same plane. At an engine speed of 1,500 r.p.m. and with the theoretical fuel quantity for no excess air, the engine developed a brake mean effective pressure of 115 pounds per square inch with a fuel consumption of 0.49 pound per brake horsepower-hour and an explosion pressure of 820 pounds per square inch. A brake mean effective pressure of 100 pounds per square inch with a brake-fuel consumption of 0.44 pound per horsepower-hour at 1,500 r.p.m. was obtained.

INTRODUCTION

The prechamber type of cylinder head for compression-ignition engines employing forced air flow for mixing fuel and air is widely used by engine builders. Considerable work that is of value to the engine designer has been done on this type of combustion chamber. (See bibliography.) Most of the work, however, has been theoretical analysis and but little has been substantiated by engine tests.

The National Advisory Committee for Aeronautics is conducting at Langley Field, Va., an investigation of the prechamber type of cylinder head for compression-ignition engines in order to determine the best arrangement of the several variables to give maximum engine performance (references 1 and 2). Two of the major variables, clearance distribution and connecting-passage size, have been investigated and the results reported in references 3 and 4.

The present work covers the research conducted in 1933 and early in 1934 and is a continuation of the investigation of the prechamber type of cylinder head. The variables investigated were: the shape of the prechamber, the shape and direction of the connecting passage, the volume of the chamber using a tangential passage, the fuel-injection system, and the direction of the fuel spray in the prechamber. The portion concerned with clearance distribution was done using tangential instead of radial passages as in the previous investigation (reference 3).

APPARATUS AND METHODS

The test equipment used for the tests herein reported was the same as that described in references 3 and 4. (See fig. 1.) The most important pieces of apparatus and the standard test conditions were as follows:

Engine	Universal test engine base; single-cylinder, 5 by 7 inches; 4-cycle
Cylinder head	N.A.C.A. design 7 with different chambers (figs. 2 and 3)
Compression ratio	13.5
Explosion-pressure indicator .	balanced-diaphragm type
Fuel	Auto Diesel, viscosity 41 seconds Saybolt Universal at 80° F.
Full-load fuel quantity (no excess air)	0.000325 pound per cycle (Air/fuel = 14.5)

Fuel temperature (room) . . .	80° F.
Engine lubricating oil temperature (out) . . .	140° F.
Cooling water temperature (out)	170° F.
Temperature of inlet air . .	95° F.

The following apparatus and test conditions remained unchanged in all tests except those in which each item was varied separately and independently:

Engine speed	1,500 r.p.m.
Fuel-injection pump	N.A.C.A. design 7A (cam-operated constant stroke)
Injection period (at 1,500 r.p.m.)	21 crankshaft degrees
Injection advance angle . . .	3° to 7° (before top center)
Fuel-injection valve	N.A.C.A. design 13 (spring-loaded hydraulic)
Spray type	conical, small angle
Nozzle type	single orifice, 0.050-inch diameter
Fuel-valve location	location 1 (fig. 3)
Valve-opening pressure	3,500 pounds per square inch

The volume of the auxiliary chamber was held at 50 percent of the total clearance throughout the majority of the tests and the connecting passage was maintained at $\frac{9}{16}$-inch diameter or the equivalent area. Although those are not the optimum proportions for auxiliary-chamber design, the sacrifice in performance is sufficiently small (references 3 and 4) to justify their use to maintain continuity throughout the entire investigation.

Connecting passage direction and shape.- The effect of connecting-passage direction in chamber and cylinder was first investigated. The passage was brought into the chamber at two different angles, i.e., radially and tangentially (fig. 2). The direction was changed by using inserts designed and constructed to permit such variations. When using the tangential passage, the direction of the passage in the cylinder was changed by rotating the chamber cap and passage insert as a unit. The increment of rotation was 36°, which was determined by the spacing of the chamber-cap studs. The tests were made by rotating the cap two increments to the right and left. The ends of the passage were successively flared to determine the effect of passage shaping.

Tests were made on a three-passage insert. Each of the three passages was designed on a proportional-area principle (reference 5) and, as nearly as the mechanical limitations of the head would permit, directed into the cylinder to serve a predetermined volume of air. The combined area of the three passages was equal to that of the standard $\frac{9}{16}$-inch diameter passage.

Chamber shape.- The effect of auxiliary-chamber shape was investigated for a limited, though carefully selected, series. A number of shapes might have been tried but analysis of the problem eliminated those obviously unsuitable for use. Analysis and test results indicated the advisability of confining the test shapes to volumes of revolution in order to conserve the residual air flow. (See also reference 2.) The spherical chamber of the first tests was changed to a disk rounded at the outside edge and arranged vertically so that the plane of the disk was parallel to the axis of the engine cylinder. The connecting passage was introduced tangentially to the disk (fig. 3). Three injection-valve holes were provided as shown and power tests were made with the fuel valve in each of three holes. After these tests the disk-shaped chamber was changed to that of a toroid by inserting a solid spool in the axis of the disk

Chamber volume.- The effect of increasing the quantity of air rotated in the prechamber was investigated by changing the volume of the chamber from 50 to 70 percent of the total clearance volume while using a tangential connecting passage. Spherical chambers were used for the tests because the least construction of new parts was required. The set-up employed in the previous tests on clearance distribution (reference 3) was duplicated and check tests were made. The tangential passage was substituted for the radial passage and tests comparable with those made using the radial passage were obtained.

The approximate direction of the air flow for both the 50-percent and the 70-percent chambers with radial and tangential passages was indicated with air-flow patterns made by extending a number of copper nibs into the auxiliary chamber of a gasket clamped between the two parts of the chamber, as described in reference 2. When taking the air-flow patterns, the engine was started from rest and brought up to 1,500 r.p.m. as quickly as possible and then shut down.

Fuel-valve location.- The variation in performance obtained by operating with the fuel valve first in the center and then in the top injection valve holes was determined for both prechambers and both connecting passages.

Injection systems.- The best combination of the previously mentioned variables was selected and used in an investigation to determine the optimum injection system for use with this assembly. Three fuel pumps were selected having widely different characteristics and were tested with different fuel-valve assemblies. The N.A.C.A. 7A and also the commercial fuel pump are cam-operated and of constant-stroke, but have different rates of displacement. The third injection pump was the N.A.C.A. 12, a cam-operated, plunger-type but with injection caused by the release of pressure stored in a reservoir of proper volume. This pump gives a much faster rate of injection and was used to obtain a shorter injection period than those given by the other two pumps. For convenience of reference to the equipment, the laboratory designations will be used. The effect of orifice length/diameter ratio was determined using the single 0.050-inch diameter orifice and the N.A.C.A. 7A fuel pump. The results obtained by using multiple orifices to distribute the fuel by injection as well as by air flow were also determined. Tests of a pintle nozzle with two different injection systems were included in the injection-system investigation.

In order to improve the inherently poor starting ability of this type of combustion chamber, a series of starting tests was made using an auxiliary valve and injecting the fuel into the cylinder instead of into the prechamber. An 0.008-inch diameter orifice nozzle was used with a valve-opening pressure of 2,500 pounds per square inch. The engine was motored by the dynamometer at gradually increasing speeds until the engine started firing and the speed could be maintained under its own power. The procedure was followed with the same fuel nozzle in the prechamber.

Test methods.- In the previously outlined tests of this investigation no attempt was made to obtain complete data for each of the variables under consideration. In most cases power tests consisted of full-load and flame-start runs, i.e., fuel quantity for no excess air and for that fuel quantity producing the first sign of flame in the exhaust pipe. These tests were made at 1,500 r.p.m. in all cases, and additional ones at 1,000 r.p.m. for some conditions. A variable fuel-quantity run was made using the best combination of the variables covered in this report.

The cylinder head consisted of the disk chamber connected to the cylinder clearance by a single round passage tangential to the disk. The N.A.C.A. 7A fuel pump used in conjunction with the single 0.050-inch diameter fuel-injector orifice having an L/D of 6 comprised the injection system.

The power data obtained in all tests were fuel consumption, brake mean effective pressure, and explosion pressure in the cylinder. The operating conditions were recorded but corrections for atmospheric pressure and humidity have not been applied to the results. The data have not been reduced to standard conditions because there is no generally accepted method of correcting the performance of a compression-ignition engine. The uncorrected performance from day to day could be checked to within ±1 percent. At full-load fuel quantity for the best combustion chamber and injection-system assembly, indicator cards were taken from the chamber and cylinder at normal injection advance angle. The injection timing and spray characteristics were observed by means of a Stroborama and recorded for all changes in the injection system.

RESULTS AND DISCUSSION

General operating characteristics.- The general operating characteristics of the engine, that is, starting ability, idling ability, cyclic regularity, and combustion shock were affected but little by any of the changes made during these tests. A change from the diesel engine fuel used in previous tests to Auto Diesel fuel reduced the tendency toward combustion shock, increased the injection advance angle range, and decreased the cyclic variation in maximum cylinder pressure from ±75 to ±40 pounds per square inch. The combustion shock common to the prechamber type of engine was present in all tests; it was not, however, considered objectionable. The combustion rates of pressure rise in the cylinder and the prechamber were, respectively, 68 and 45 pounds per square inch per degree at 1,500 r.p.m. with the best combination of variables covered in this report. The rates of pressure rise reported in the previous publications of this series were approximately 86 and 75 pounds per square inch per degree at 1,500 r.p.m. for cylinder and chamber, respectively.

Starting at 70° F. could be effected by motoring the engine at speeds varying from 400 to 600 r.p.m.; hot starting (immediately after power running) could be obtained in two revolutions of the crankshaft (one compression stroke) under all conditions. The minimum idling speed obtainable varied from 300 to 400 r.p.m. Variations in the combustion-chamber shape did not appreciably affect the combustion shock but changes in the injection characteristics had a noticeable effect upon the combustion sound.

Marked improvement in the ability of the engine to start when at a temperature of about 70° F. was obtained by injecting into the cylinder. By the employment of a nozzle with a single 0.008-inch diameter orifice and the injection of only a small percentage of full-load fuel quantity, starting could be obtained by motoring the engine at from 200 to 300 r.p.m. whereas with injection into the chamber using the same nozzle a speed of 600 to 700 r.p.m. was required. The improvement in starting is due to a higher temperature in the cylinder, which is caused by a smaller heat loss from the compressed air charge in the cylinder.

Effect of passage direction and flaring.- The purpose of directing the passage tangentially to the chamber instead of radially was to create a high-velocity, rotational, residual air flow in the auxiliary chamber to improve the fuel and air mixing. Figure 4 shows that increasing the rotational air flow, as by using a tangential passage, does improve the engine performance.

As discussed in a later section of this report, the radial passage permitted a slight tangential and rotational air flow in the chamber; the engine performance of figure 4 is therefore for different intensities of rotational air flow. The performance point (a) is for the radial passage and domed piston crown (reported in reference 4) which gave a slight tangential and rotational air flow in the chamber. As part of an investigation now being extended, the top of the domed piston crown was made flat so that only the edge of the piston crown conformed to the contour of the cylinder head and most of the cylinder clearance was over the flat of the piston crown. This altered clearance shape gave the performance indicated by point (b). The increase from (a) to (b) is probably the result of two causes: First, the air massed over the piston crown center is more readily reached and burns more efficiently than if it were distributed over the entire crown; second, in the region of the connecting passage the displacer action of the piston edges, on approaching top center, can increase the tangential and rotational air flow in the auxiliary chamber. The tangential passage gives the maximum tangential and rotational air flow which in turn causes a further increase in engine performance indicated by point (c).

The effect of flaring the ends of the connecting passage is shown by (d) and (e). Rounding the cylinder end of the connecting passage increased the performance presumably by allowing the issuing jet to spread throughout more of the cylinder clearance. Rounding the chamber end of the passage evidently decreased the effective air swirl in the chamber because both indicated and brake performance were decreased. As the pumping losses, f.m.e.p., also decreased the brake performance was reduced but little.

The effect of passage direction in the cylinder was investigated using the disk-shaped auxiliary chamber discussed later. The results are therefore to be considered independently of the first passage-direction tests. The degrees indicated along the abscissa of figure 5a show the rotation of the chamber cap and the insert toward and away from the exhaust valve. The change being made in this manner, all other conditions were maintained and the effect of passage direction in the cylinder is the only variable to be considered. The curves show that the power decreases for a change in passage direction on either side of the center position. The carbon formation on the piston crown showed that the desired swirl in the cylinder was set up but the results indicate that the swirl was ineffective in improving combustion of the cylinder air and instead hindered the fuel in reaching the unburned cylinder air. This condition, of course, means that the burning occurs later in the stroke with a resulting decrease in cycle efficiency.

Figure 5b shows the results of tests on the three-passage insert. The most interesting feature of these curves is the friction mean effective pressure shown for the three-passage insert, which is no greater than that for the single-passage inserts. A small decrease in power resulted from the use of three passages either because the passages were too short to direct effectively the gases in the cylinder or because the three passages entering the prechamber caused a disturbance in the air flow in the chamber that adversely affected the performance. The test results obtained did not warrant a more comprehensive investigation.

Effect of prechamber shape and fuel-valve location.- Figure 6 shows the effect of changing the prechamber shape from that of a sphere to a disk of equal volume. The effect of fuel-valve location in the disk chamber is also shown. The disk chamber, with the injection valve in the center hole, gives an improvement in performance over the spherical chamber under similar conditions. This improvement can be attributed to the fact that in the disk chamber the low-velocity zones common to the spherical chamber are removed and all the rotating mass of air is put into the zone of the single fuel spray and the connecting passage. This relation of chamber shape and fuel spray evidently results in better mixing in the prechamber with the resultant improved performance.

The toroid chamber was used to intensify the air flow still further by removing the air in the low-speed center section of the disk. Because the preliminary power tests did not show an improvement in performance, a comprehensive investigation was not conducted and the test data obtained were not considered of sufficient value to present. It was believed that the interference with the air flow and fuel spray caused by the insertion of the solid center in the prechamber more than overbalanced the benefits of removing the low-velocity air from the center of the disk. It is possible that the toroid chamber instead of increasing the velocity of the air decreased it owing to the greater surface-volume ratio, which increased the frictional resistance.

The effect of fuel-valve location is also shown on figure 6. The great difference in maximum power for the three fuel-valve holes provided in the disk chamber shows the importance of the position of the fuel spray relative to the air movement. The best performance was obtained with the spray from the single-orifice nozzle directed in the same plane with the air flow and at only a small angle from the direction at right angles to the air flow. The spray was directed toward the connecting passage. The worst performance was obtained with the fuel valve in the lowest position. (See fig. 3.) In this position the spray is injected counter to the air flow and should penetrate directly through the passage to the cylinder. The purpose of this arrangement was to obtain a rich mixture adjacent to the passage ready to be ejected into the cylinder by the burning in the chamber. With the chamber cap rotated 180°, the lower valve hole was in approximately the same position but the spray was directed not through the passage but up above the entrance to the passage and the spray was at an angle to the air flow and not counter to it. This condition gave an improvement in performance of about 10 pounds per square inch brake mean effective pressure over that originally obtained with the fuel valve in the lowest position. The results of these tests on fuel-valve position led to a more comprehensive investigation of this variable.

Effect of chamber volume and fuel-valve location.- Analysis of previous work indicated that the greater the amount of air in motion the better would be the mixing of the fuel and air and consequently the better the performance. A tangential passage in conjunction with a chamber that contained a larger percentage of the clearance volume was used to increase the quantity of air in motion. Figure 7 shows that this analysis was correct for spherical chambers because, with the fuel valve in the center hole, the increase in the performance with increase in chamber volume was greater when using a tangential passage than when using a radial passage. The increase in rotational, and probably residual, air-flow velocity due to the tangential passage was sufficient to make an appreciable difference in the performance. The investigation was made with spherical chambers because their use entailed the manufacture of only one new part and, although the maximum performance would be less than with the disk chambers, the indicated trend should be the same for both auxiliary-chamber shapes.

The tangential connecting passage was used because introducing the air tangentially to a volume of revolution assisted in setting up a rotational swirl in the chamber which should persist after the piston had reached the upper limit of its travel. This residual air flow was believed to be the cause of the increased power and every attempt was made to intensify and preserve the flow. This theory could not be proved because there are no means available for measuring the velocity of the flow, although the predominating direction of the air flow was determined by means of the air-flow patterns. The tangential passage was found to give air flow in the prechamber that was truly a rotational swirl. The copper nibs of the air-flow pattern on the axis perpendicular to the axis of the connecting passage were not bent, while those nibs directly opposite the passage and 180° therefrom were bent through a large angle and in a direction that indicated a rotation of the zone into which the passage enters.

The indicated rotational air flow in the chamber using the tangential passage was to be expected, but the air-flow pattern taken using a radial passage to the same chamber also showed rotational air flow but in the opposite direction. The intensity of the flow, as indicated by the angle of bend of the copper nibs, was not so great as that obtained using the tangential passage. The radial passage did not give true radial flow because it was too short to direct the air properly. This possibility was considered before the passage was constructed and the passage was made as long as the cylinder head would permit. In a direction parallel to the axis of the cylinder, however, there is a small projection of the passage cross section through which the air could flow directly into the chamber without coming in contact with the walls of the passage. The tendency for the air from the cylinder to pass directly into the chamber must have been sufficient to displace the direction of flow from the axis of the passage and cause a rotational swirl in the chamber opposite in direction to that induced by the tangential passage.

Since the forced air flow with both passages is tangential, the difference in performance shown for the different fuel-valve locations is more readily explained (fig. 7). It was found that with the spherical chambers the performance was improved by injecting the fuel at the point on the circumference of the chamber nearer the connecting passage. The upper hole 1 was better when using the radial passage and the center hole 2 better when using the tangential passage. (See fig. 2.) In the disk chamber, injecting the fuel near the passage mouth but directly toward the passage gave the worst results.

Effect of injection systems.- Figure 8 shows the results of the injection-system tests. The object of these tests was to obtain a fuel spray whose characteristics best suited the 50-percent vertical disk chamber and tangential passage, the arrangement that had given the best performance for this size of chamber. It should be noted that, for the combustion-chamber arrangement employed for these tests, the optimum performance was obtained with an injection period of 21 crankshaft degrees. With but few exceptions, the engine performance decreased for injection periods either longer or shorter than this value. The longer injection period caused the combustion of part of the fuel to occur too late in the cycle. The shorter injection period caused too high a rate of pressure rise, because too much fuel was in the cylinder when the fuel ignited. For this reason the permissible injection advance angle was too late, with the resulting poor performance.

The injection period was the only spray characteristic accurately measured during the injection-system tests. The other characteristics such as distribution of fuel in the spray, spray-cone angle, and atomization should not be critical in this type of combustion chamber because there should be sufficient air flow in the auxiliary chamber to insure good mixing. Penetration and spray-cone angle have some effect, however, as shown by the tests on orifice length-diameter ratio (L/D). In this case the best performance and quietest operation were obtained with an L/D of 6, which should give the greatest penetration and smallest spray-cone angle of any nozzle tested.

The performance obtained with the multiple-orifice nozzles giving fan sprays is not shown on the curves because there was a slight decrease in power at test speeds. There was an improvement, however, in the starting and idling characteristics. This phenomenon can also be attributed to air flow, or rather the lack of air flow, at low engine speeds. The small orifices of the multiple-orifice nozzle assist starting and slow-speed running by giving good dispersion. The increased dispersion of the multiple-orifice nozzle over that of the single-orifice nozzle is not effective when the engine speed is high enough to give high-velocity air flow in the auxiliary chamber while the greater penetration of the single-orifice nozzle is effective.

Variable fuel-quantity tests.- The results of the power tests made with the best combustion-chamber shape and fuel-injection system tested are shown in figure 9. The curve of mean effective pressure against fuel quantity shows the characteristic straight line at small fuel quantities, but, for the combustion chamber under test, this condition continues to comparatively large fuel quantities. The mean effective pressure varies linearly with the quantity of fuel injected up to a fuel quantity of 2.25×10^{-4} pounds per cycle (air-fuel ratio approximately 23 : 1). The curve begins to droop at this point and when the fuel quantity is increased to 2.90×10^{-4} flame appears in the exhaust. With this type of combustion chamber, the flame appears in the exhaust before smoke. Both flame and smoke can be seen at full-load fuel quantity.

It seems reasonable to conclude that, as more than 50 percent of the air is efficiently burned, most of the chamber air is consumed and the air not utilized is in the more inaccessible cylinder clearance. Future investigations will be directed toward making the fuel reach more of the cylinder air.

The points of figure 9 that do not fall on the curve represent the data obtained with the injection advance angle increased by 4^{o}. It will be noted that the explosion pressure increased out of proportion to the increase in engine performance. For this reason, the injection advance angle was not further increased. In all except these tests the injection advance angle was determined by the combustion sound. In these tests, although the sound of combustion became m ore intense, the condition was not dangerous.

At full-load fuel quantity during the variable-load run, made with the best combustion chamber shape and fuel-injection system, indicator cards were taken from the chamber and cylinder (figs. 10 and 11). These cards are typical of the indicator cards obtained from this engine. The rates of pressure rise determined from the indicator diagrams are 68 and 45 pounds per square inch per degree for the cylinder and prechamber, respectively.

CONCLUSIONS

From the results of the investigation to date on the auxiliary-chamber type of cylinder head, several optimum conditions are evident. For maximum performance of this engine having a 5-inch bore and a 7-inch stroke the prechamber should be as large as possible, shaped as a disk, and connected to the cylinder clearance by a single passage whose area is governed by the performance at the designed engine speed. (See reference 4.) The passage should enter the prechamber tangentially so as to cause a strong rotational air flow. The passage should enter the cylinder radially and should be flared to spread the issuing gases over the piston crown. The injection period of the fuel spray should be approximately 21 crankshaft degrees. The nozzle used should have a single round-hole orifice of approximately 0.050-inch diameter and an orifice length-diameter ratio of approximately 6 to give a narrow spray cone with high penetration. This spray should be directed across the disk chamber toward the mouth of the connecting passage. The fuel-valve location and spray direction greatly affect the engine performance.

It was found possible to improve the starting of the prechamber engine by using an auxiliary nozzle to inject a small percentage of the full-load fuel quantity into the cylinder clearance.

The changes in combustion-chamber design reported in this work have improved the engine performance at 1,500 r.p.m., full-load fuel quantity, from 98 pounds per square inch brake mean effective pressure and 0.57 pound brake fuel consumption to 115 pounds per square inch brake mean effective pressure and 0.49 pound brake fuel consumption.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 12, 1934.

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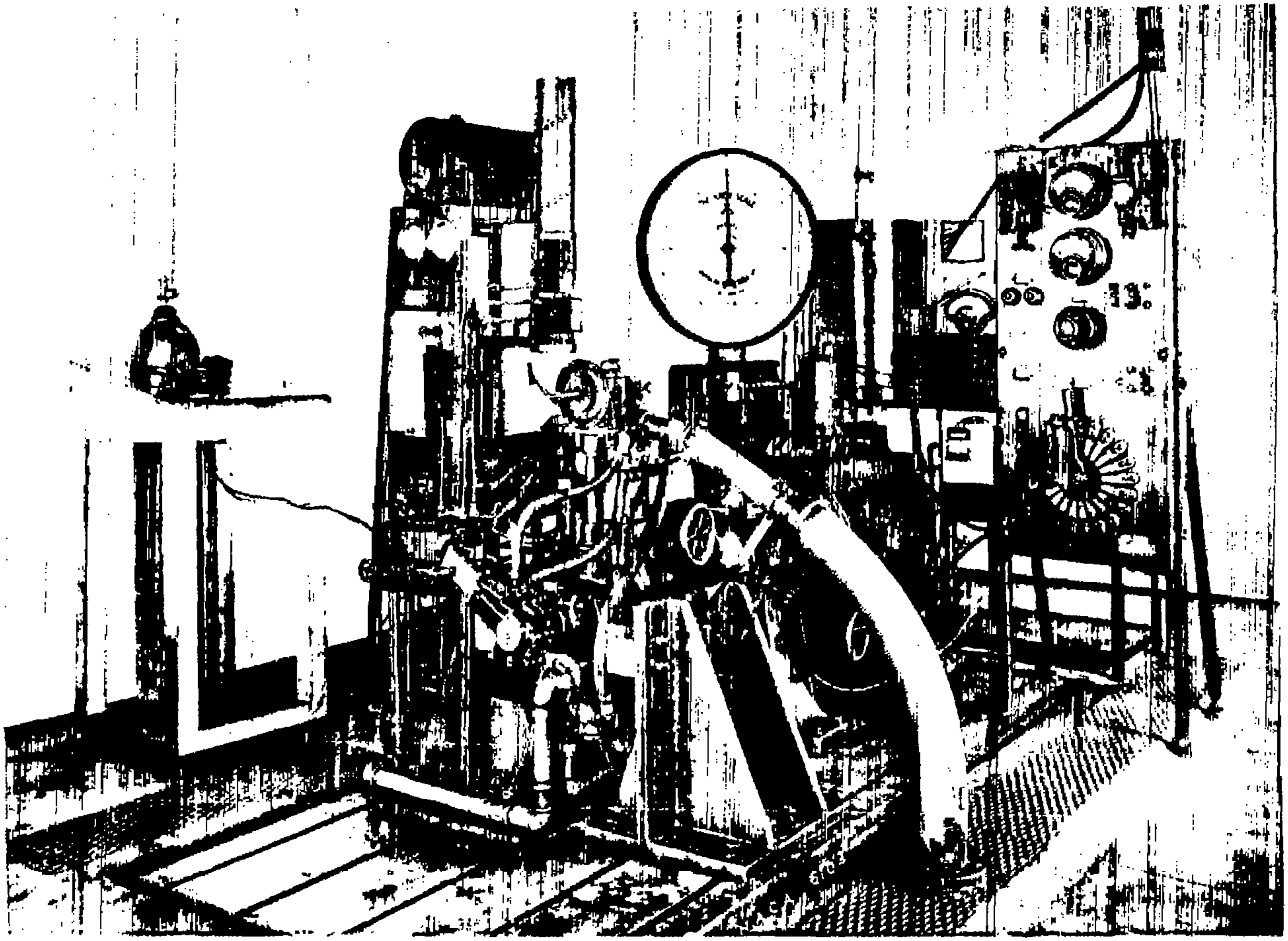

Figure 1.- Single-cylinder research engine and testing equipment.

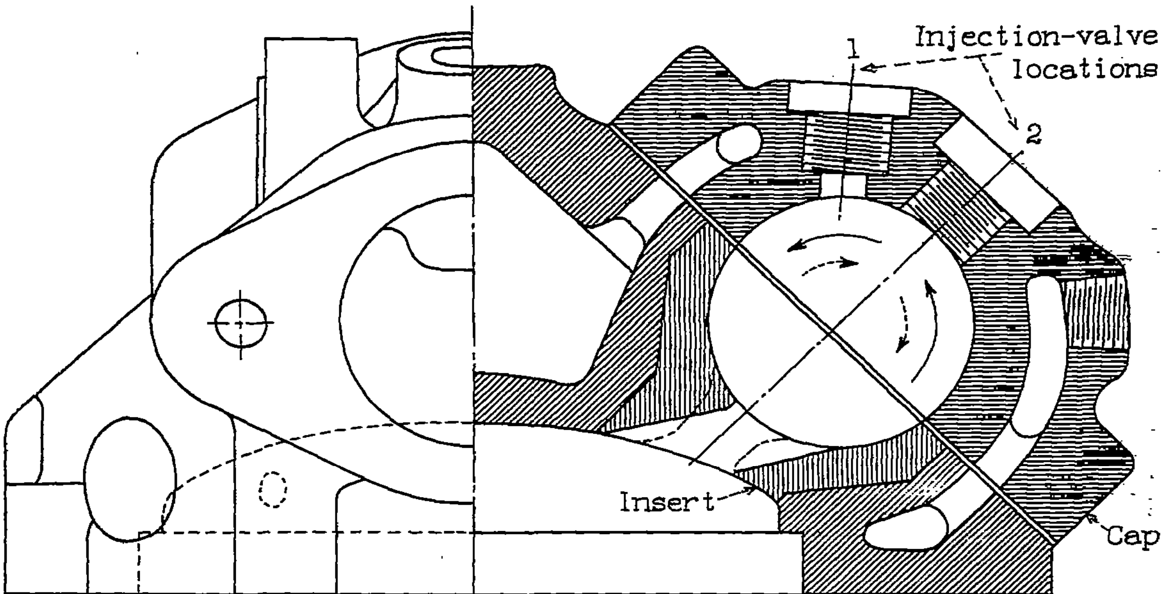

Figure 2.-N.A.C.A. cylinder-head design 7 showing spherical prechamber, with tangential and radial (dotted) passages.

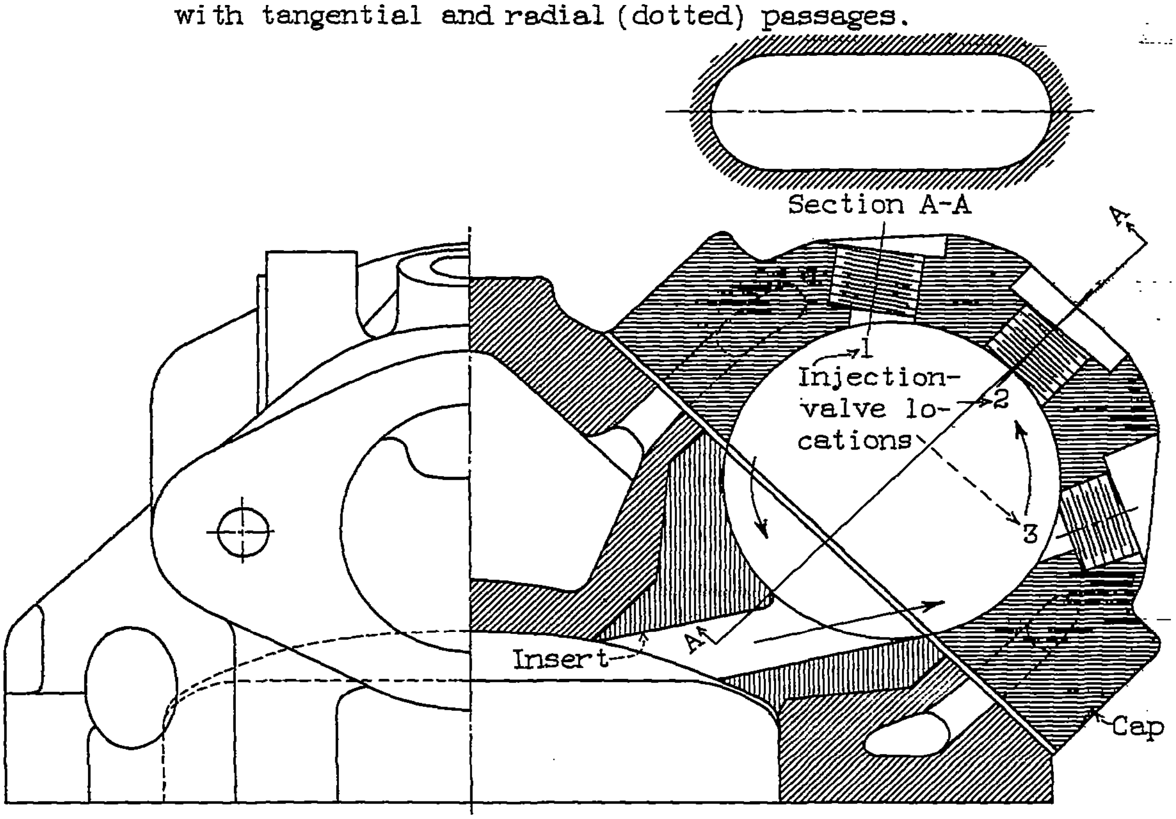

Figure 3.-N.A.C.A. cylinder-head design 7 showing disk-shaped prechamber.

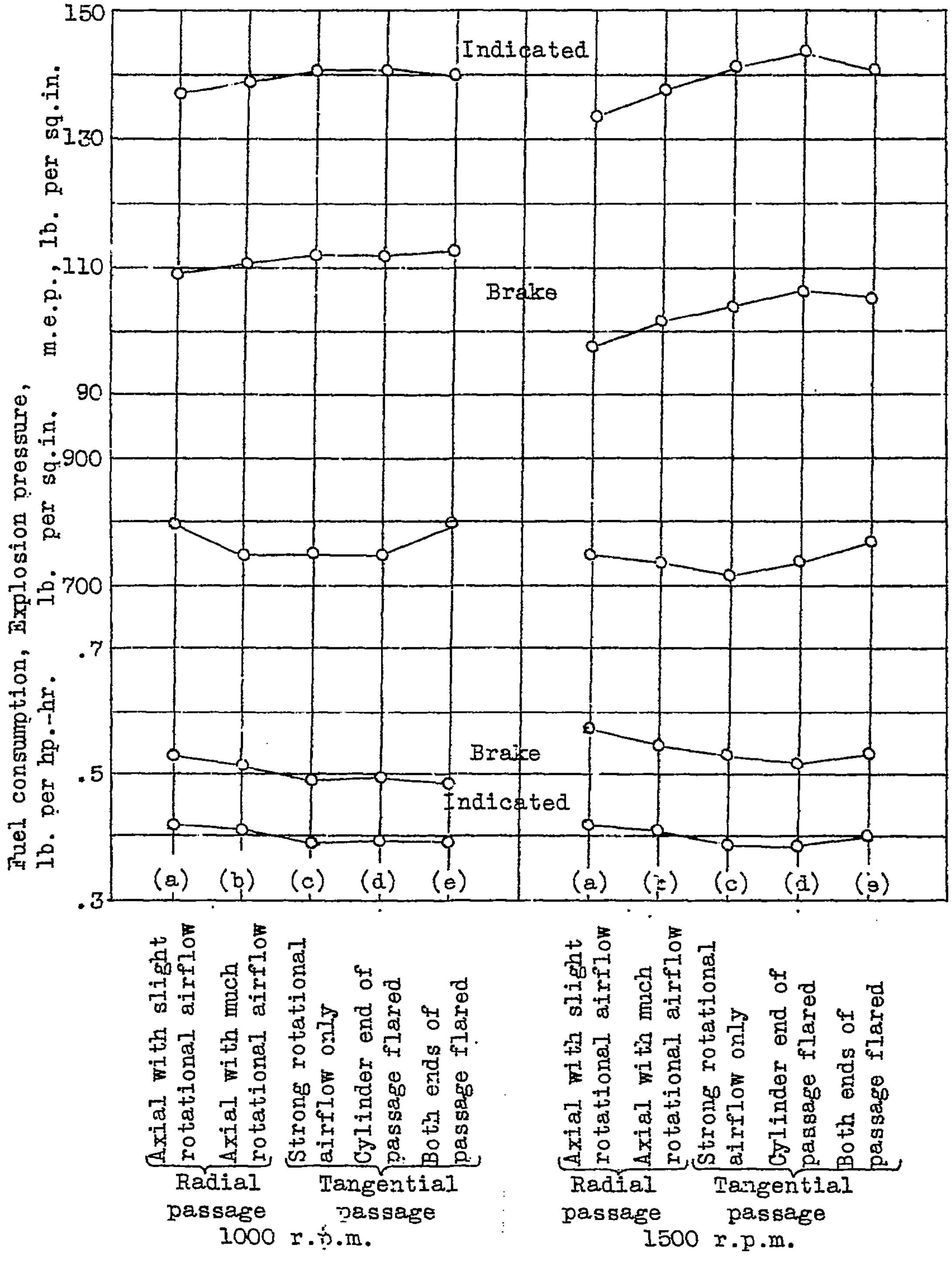

Figure 4.-Effect of passage direction and flare on engine performance. The 50-percent spherical prechamber. Connecting passage as noted. N.A.C.A. 7A fuel pump. N.A.C.A. 13A fuel valve. The 0.050-inch nozzle. Ratio L/D, 2.5 .

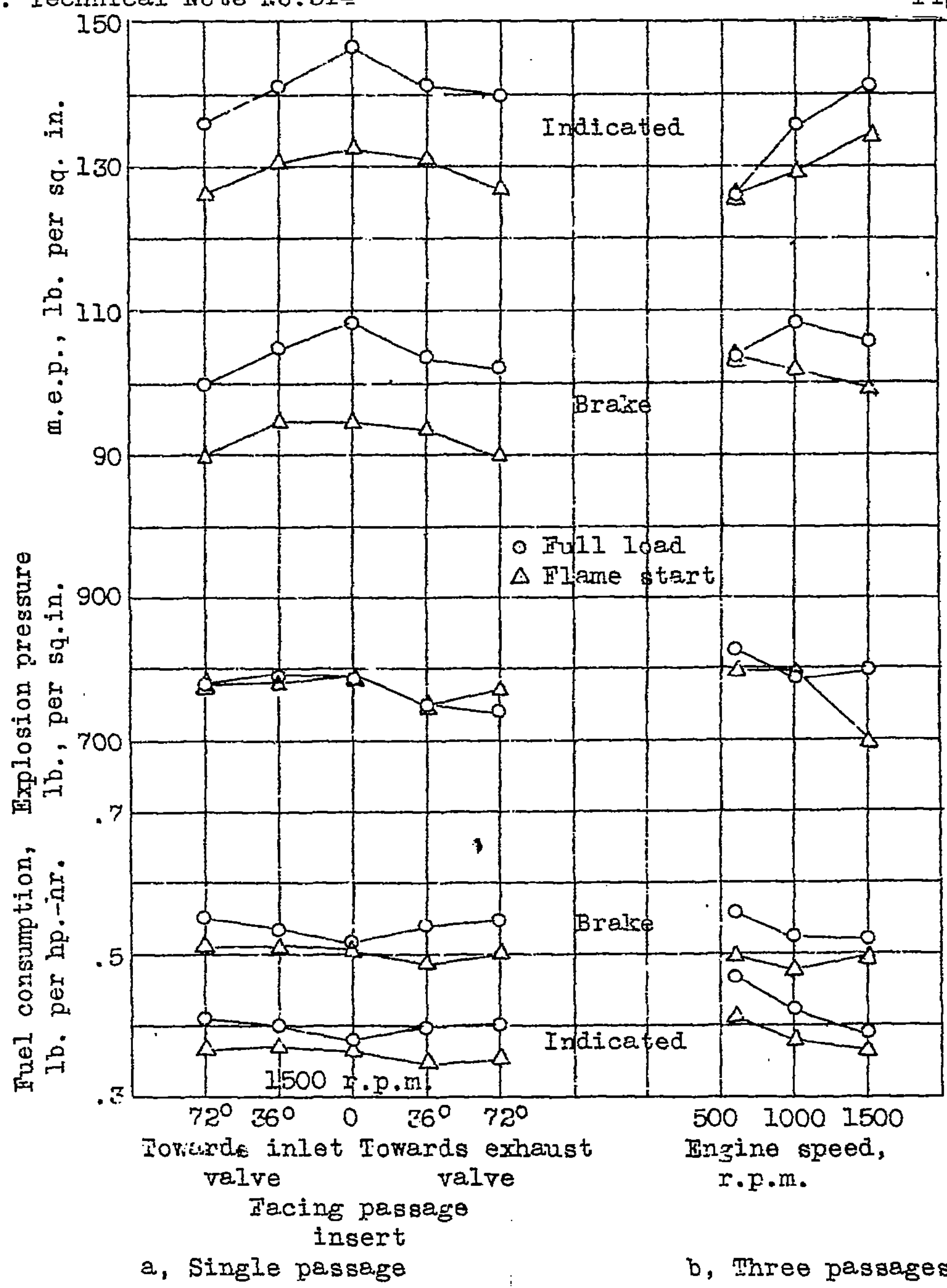

Figure 5.-Effect of passage arrangement on engine performance. The 50-percent disk prechamber. Connecting passage as noted. N.A.C.A. 7A fuel pump. N.A.C.A. 13A fuel valve. The 0.050-inch nozzle. Ratio L/D, 2.5 .

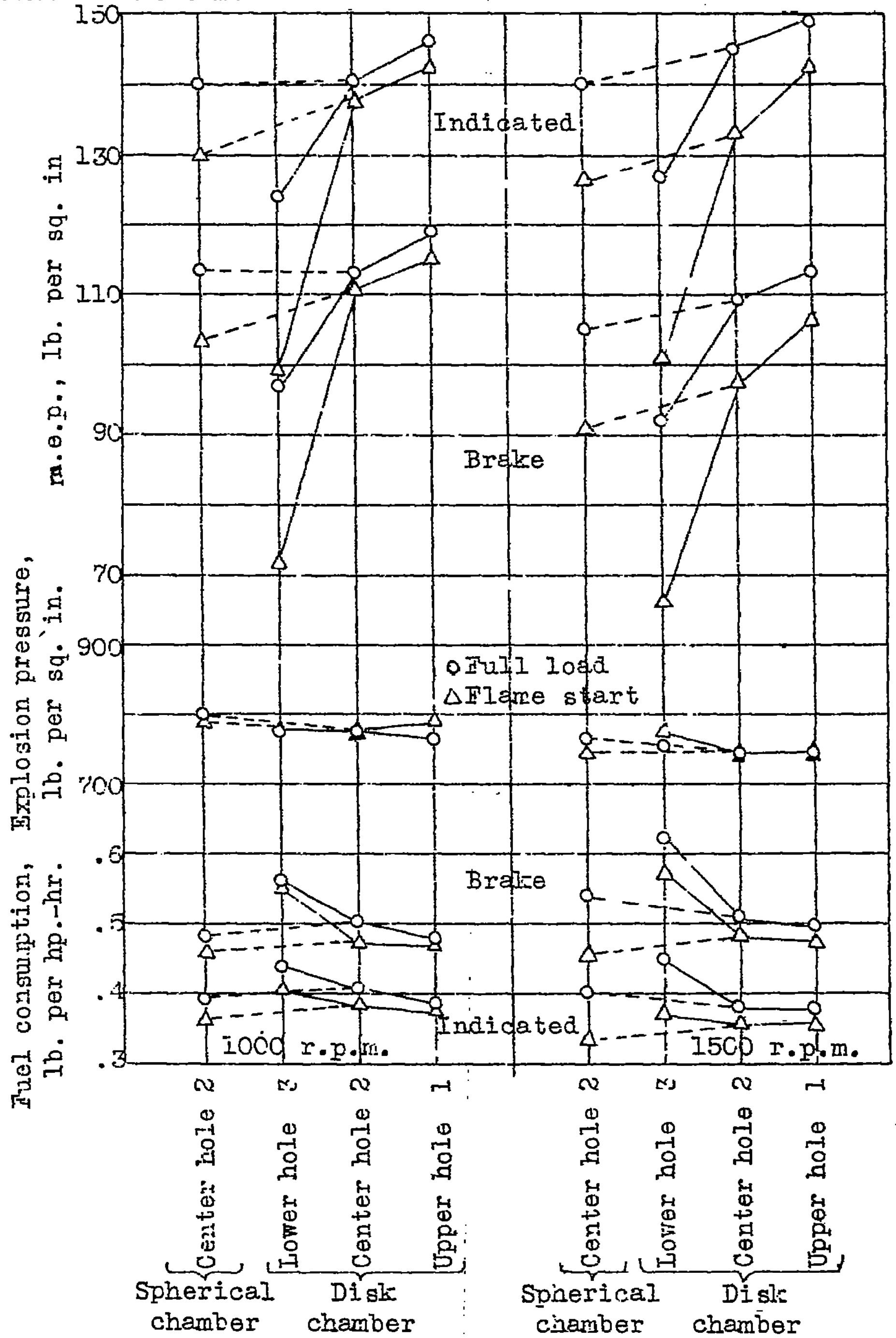

Figure 6.-Effect of prechamber shape and injection-valve location on engine performance. Prechamber as noted. Single tangential connecting passage. N.A.C.A. 7A fuel pump. N.A.C.A. 17A fuel valve. The 0.050-inch nozzle. Ratio L/D, 6 .

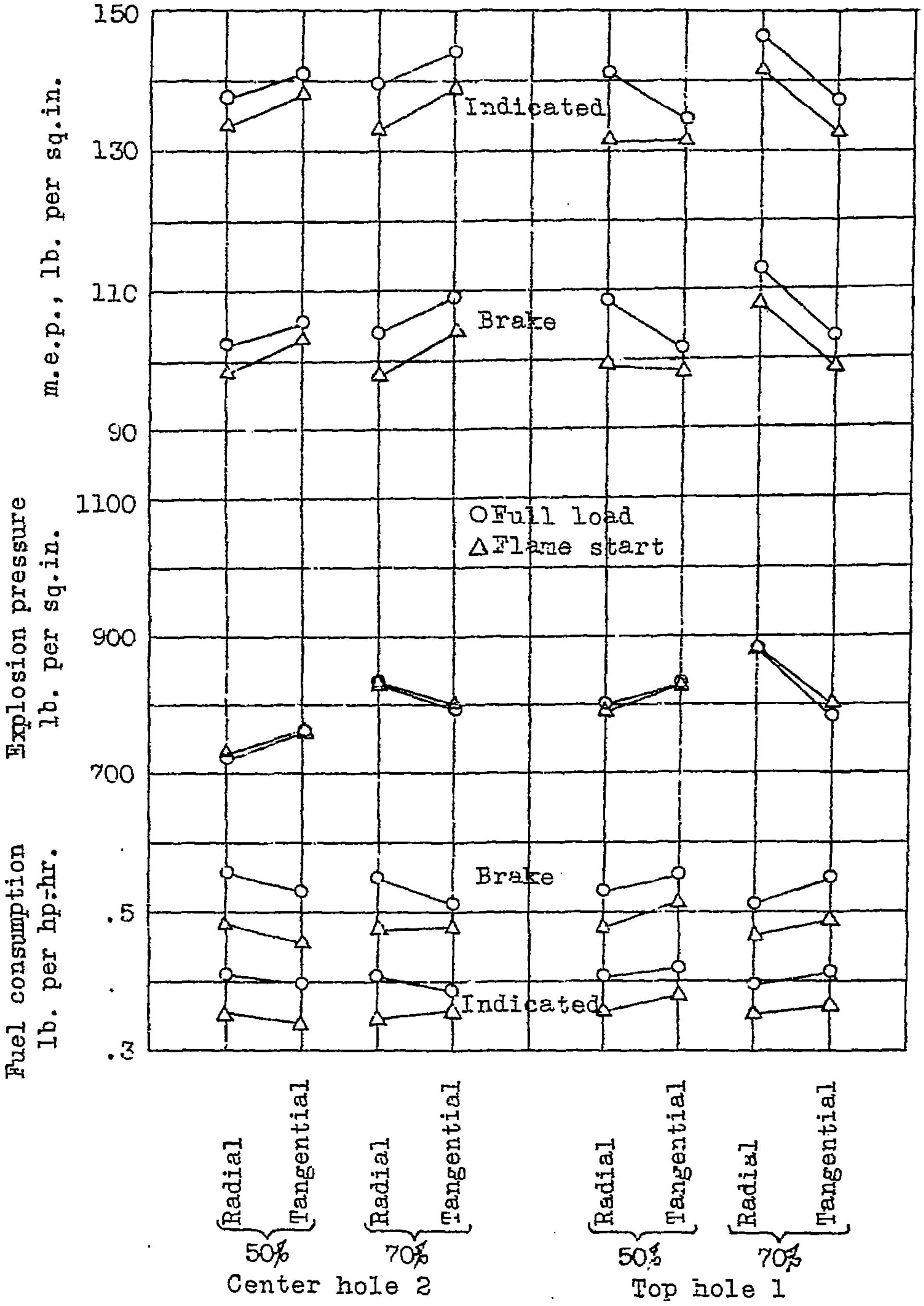

Figure 7.- Effect of passage direction, prechamber volume, and fuel-valve location on engine performance. Spherical prechambers. Connecting passage as noted. N.A.C.A. 7A fuel pump. N.A.C.A. 13A fuel valve. The 0.050-inch nozzle. Ratio L/D,6.

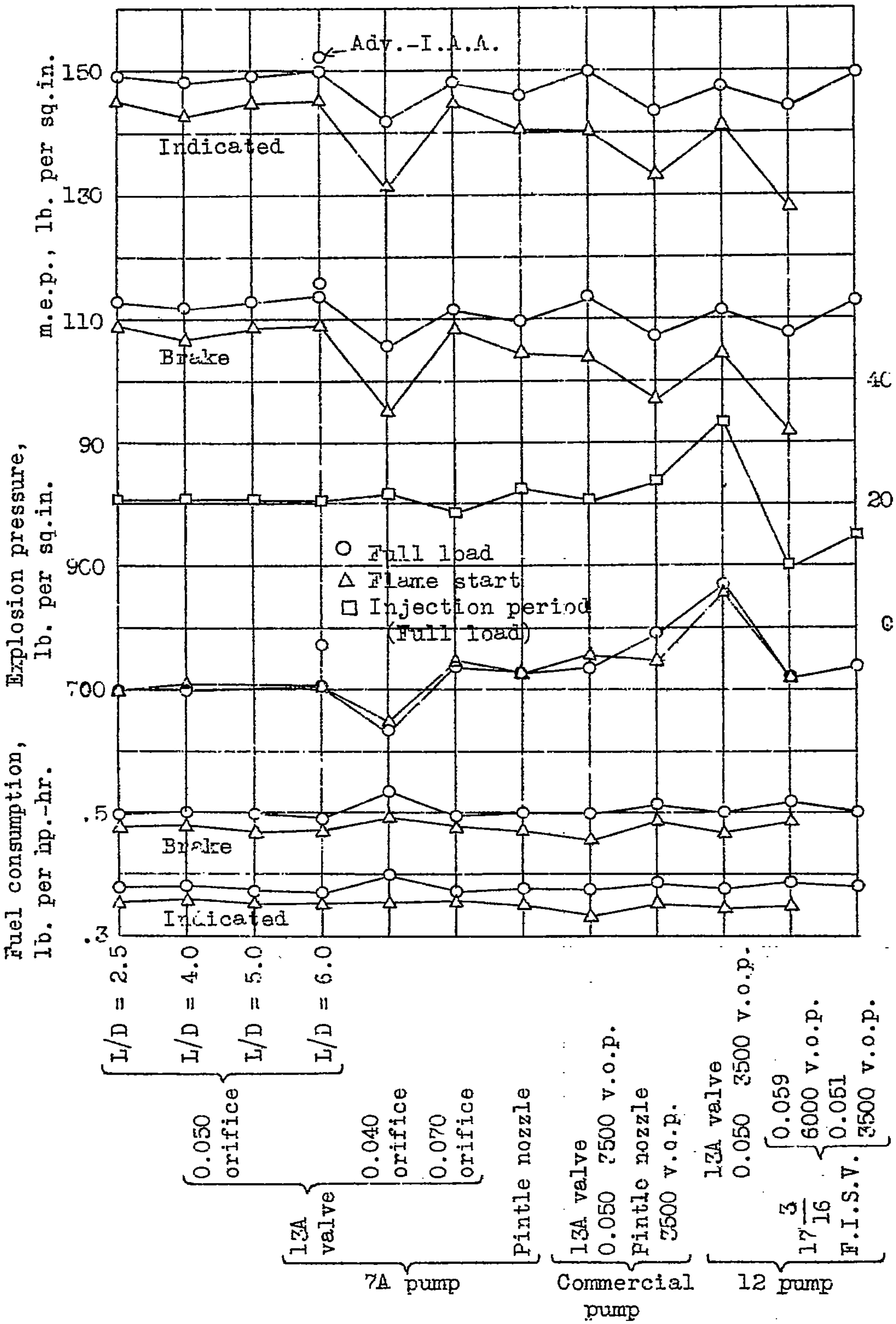

Figure 8.- Effect of injection systems on engine performance. The 50-percent disk chamber. Single tangential connecting passage. Injection system as noted.

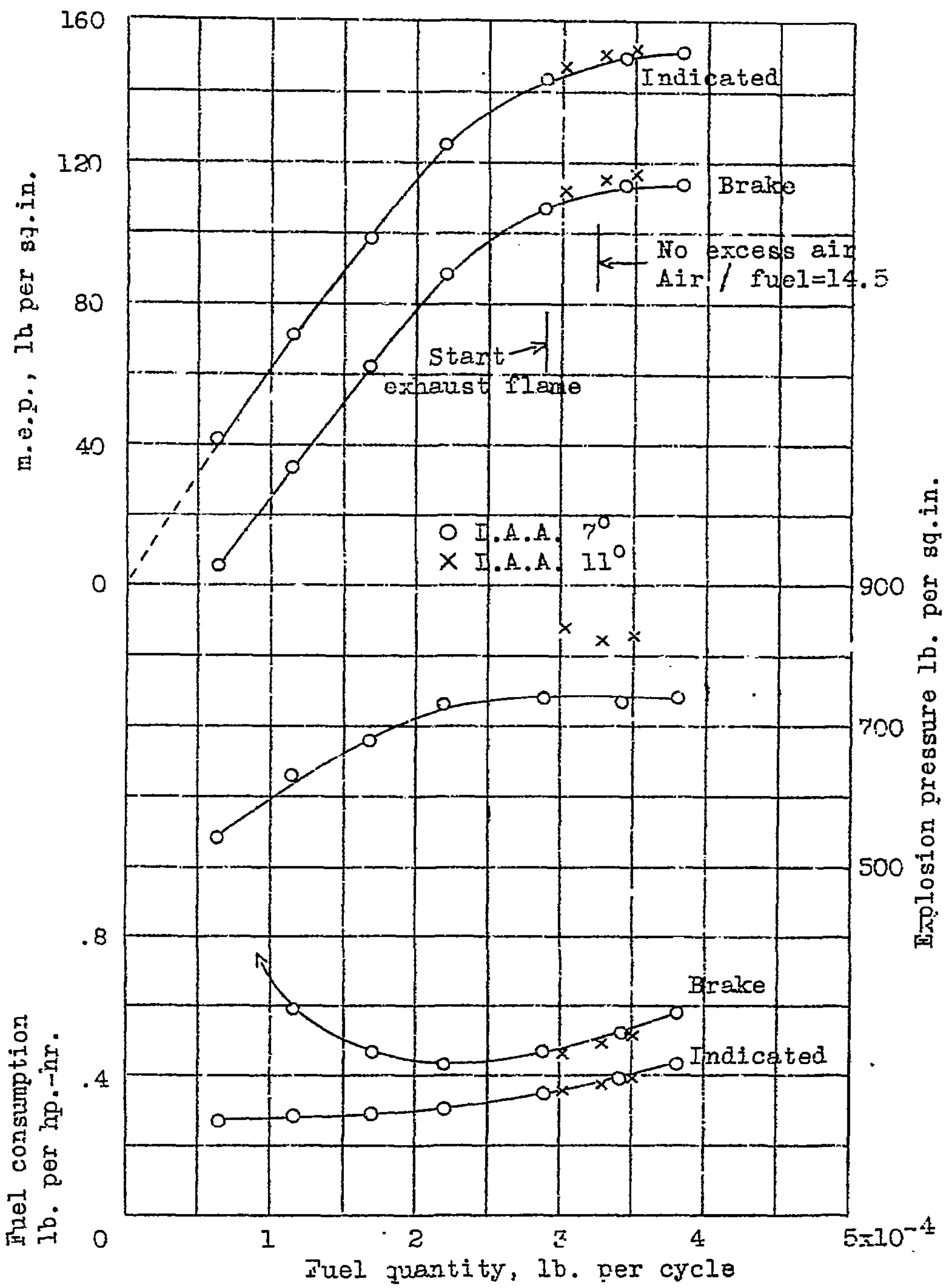

Figure 9.- Effect of fuel quantity on engine performance at 1,500 r.p.m. The 50-percent disk chamber. Single tangential connecting passage. N.A.C.A. 7A fuel pump. N.A.C.A. 13A fuel valve. The 0.050-inch nozzle. Ratio L/D,6.

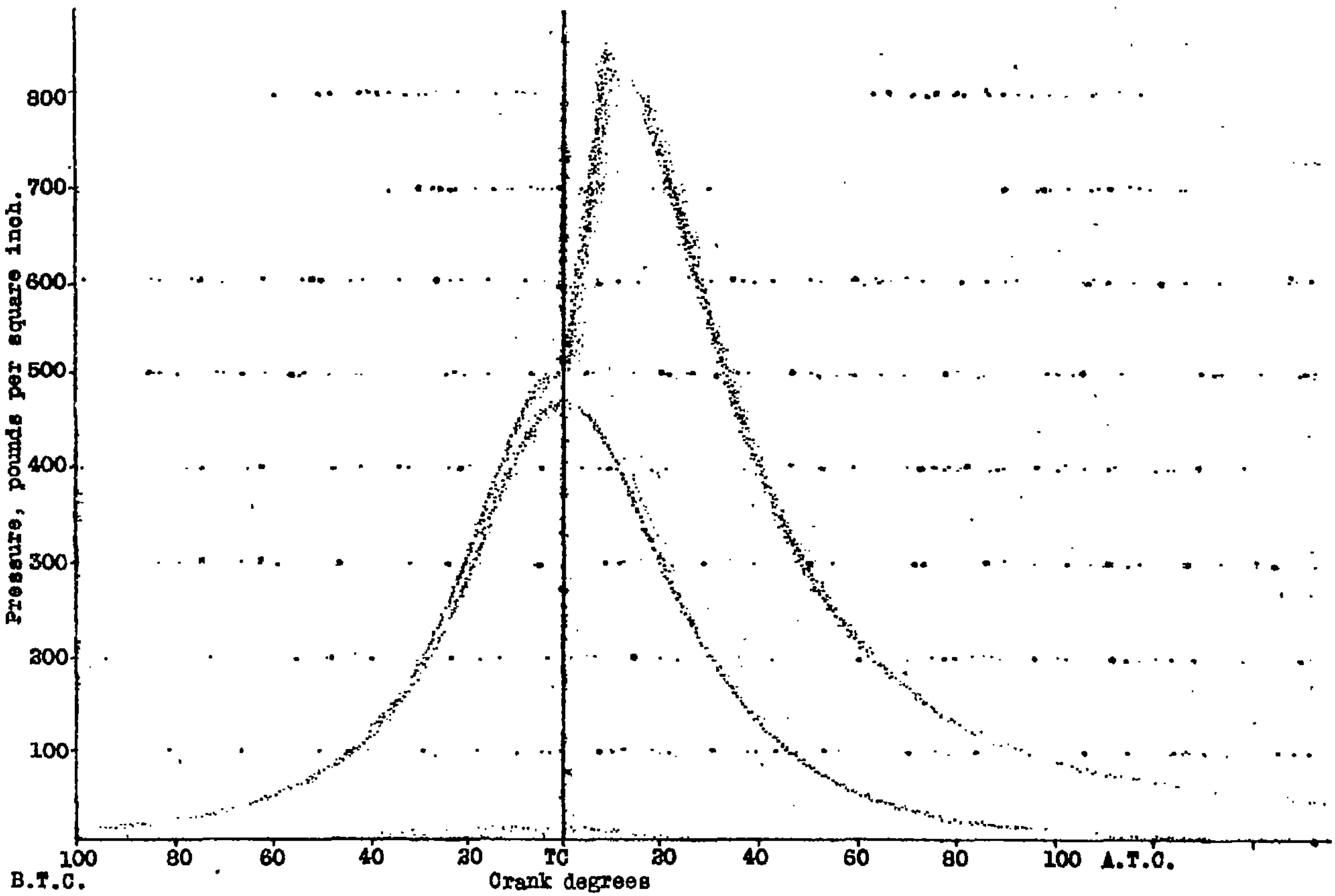

Figure 10.- Typical power and motoring indicator cards taken from the chamber. Full-load fuel quantity. The 50-percent disk chamber. Single tangential connecting passage. N.A.C.A. 7 A fuel pump. N.A.C.A. 13 A fuel valve. The 0.050-inch nozzle. Ratio L/D, 6.

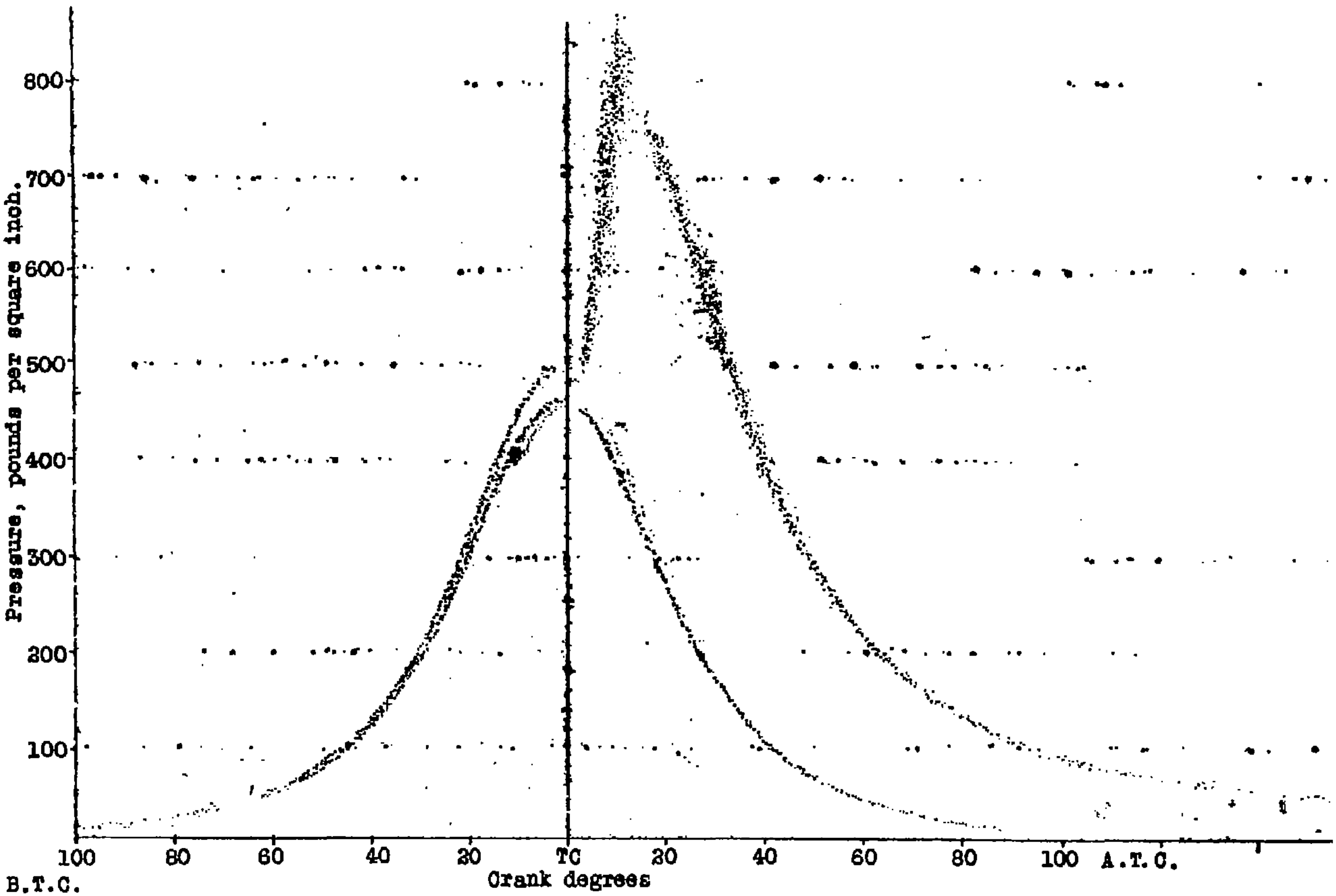

Figure 11.- Typical power and motoring indicator cards taken from the cylinder. Full-load fuel quantity. The 50-percent disk chamber. Single tangential connecting passage. N.A.C.A. 7A fuel pump. N.A.C.A. 13A fuel valve. The 0.050-inch nozzle. Ratio L/D, 6.